


Description 

**Piezoactuator and method for production of the piezoactuator**

The invention relates to a piezoactuator comprising at least one stacked piezoelement with at least two electrode layers, arranged one over the other along a stacking direction of the piezoelement, at least one piezoelectric layer, arranged between two of the electrode layers, and at least one pretensioning device, for introduction of force into a volume of the piezoelectric layer by means of at least one force introduction surface on the piezoelectric layer, which is arranged on at least one of the surface sections facing the pretensioning device. A method for production of the piezoactuator is also specified.

A piezoactuator of the said kind is known from US 6 274 967 B1. The piezoactuator has a piezoelement constructed in multiple layers. In such a piezoelement a plurality of electrode layers and piezoelectric layers are stacked alternately one over the other. The piezoelectric layers consist of a piezo-ceramic material. The pretensioning device for the introduction of force into the respective volume of the individual piezoelectric layers consists of a hollow, cylindrical spring element, an actuator cover and an actuator bottom plate. The piezoelement together with both its end faces is pre-tensioned between the actuator cover and the actuator bottom plate by means of the spring element. A force is introduced into a total volume of each of the piezoelectric layers with the aid of the pretensioning device. A unidirectional compressive tension is applied to the piezoelectric layers along the stacking direction. Introduction of the force or compressive tension causes a switching of domains. The domains are preferably polarized transverse to the direction of force introduction or the stacking direction.

In order to introduce the force into the total volume of each of the piezoelectric layers, each piezoelectric layer has surface sections which face away from one another and are aligned parallel to the end faces of the piezoelement. These surface

sections face toward either the actuator cover or the actuator bottom plate of the pretensioning device. The surface sections are the same size as the end faces of the piezoelement. The force is introduced into the total volume of the piezoelectric layer in each case via the total surface section of the piezoelectric layer.

The known piezoactuator is used for example to activate an injection valve in what is known as a common rail injection system. For this purpose it is necessary that both a defined displacement and a defined force can be transmitted along the stacking direction.

A dimension for the displaceability of the piezoelectric material in the direction of an applied electrical field strength is known as the piezoelectric loading constant  $d_{33}$ . One possible way to obtain a relatively large displacement at a given value of  $d_{33}$  would be to increase the total height of the piezoelement. Alternatively a relatively large displacement can be obtained by introducing a force or a unidirectional compressive tension along the stacking direction of the piezoelement. For this purpose the statistically distributed ferro-electrical domains are switched by means of a so-called ferro-elastic process preferably transverse to the applied compressive tension or transverse to the stacking direction, for example in an unpolarized piezoelement. This gives rise to a permanent shortening of the piezoelement. This shortened piezoelement is electrically activated. Applying an electrical field parallel to the stacking direction causes domain switching with a preferred direction parallel to the applied electrical field. Significantly more domains are switched in comparison with the piezoelement that has no compressive pretensioning. As a result there is a greater displacement of the piezoelement in the stacking direction when compared to the piezoelement that has no compressive pretensioning.

For it to be possible to use this means to obtain greater

displacement in a stacked piezoelement constructed in multiple monolithic layers, a force of over 100 N would be necessary in the case of, for example, a basic piezoelement surface area of 1 x 1 mm<sup>2</sup>. In the case of a basic surface area of 5 x 5 mm<sup>2</sup> a force  
5 of around 2.5 kN would be needed. This can only be accomplished with the aid of a stiff spring with a corresponding loss of no-load displacement.

However, using compressive pretensioning to increase the displacement is not only a problem for piezoactuators on the  
10 macro-scale. In particular, using compressive pretensioning to increase displacement is unsuitable for producing a piezoactuator with a relatively large displacement and force translation on the micro-scale.

The object of the invention is to provide an actuator which can  
15 be used as a micro-actuator and which has a very large relative displacement in comparison with the known prior art.

This object is achieved by means of a piezoactuator comprising at least one stacked piezoelement with at least two electrode layers, arranged one over the other along a stacking direction of  
20 the piezoelement, at least one piezoelectric layer, arranged between two of the electrode layers, and at least one pretensioning device, for introduction of force into a volume of the piezoelectric layer by means of at least one force introduction surface on the piezoelectric layer, which is  
25 arranged on at least one of the surface sections facing the pretensioning device. The piezoactuator is characterized in that the force introduction surface is smaller than the surface section of the piezoelectric layer and that the volume is a partial volume of the piezoelectric layer. This partial volume is  
30 effective as an actuator.

The object is further achieved in that a method is specified for producing the piezoactuator by introducing a force into the partial volume of the piezoelectric layer by means of the force introduction surface on the piezoelectric layer. The force is

introduced in such a way that, in the partial volume of the piezoelectric layer, a polarization is generated transverse to the stacking direction. The polarization of the domains in the partial volume is preferably oriented transverse to the stacking  
5 direction. This makes the partial volume effective as an actuator.

Preferably the piezoelement is in a non-electrically activated state. No electrical field is applied. Along the stacking direction, the pretensioning device introduces indirectly via the  
10 force introduction surfaces a locally limited force or a locally limited mechanical compressive tension in a partial volume of the piezoelectric layer. Due to this mechanical compressive tension, the ferro-electrical domains statistically distributed in the partial volume of the piezoelectric layer in an unpolarized  
15 piezoelectric layer or oriented parallel to the pressure introduction in a normally polarized piezoelectric layer are switched in a preferred direction transverse to the applied mechanical compressive tension. This causes a permanent deformation or rather shortening of the piezoelectric layer in  
20 the region of the partial volume. A thickness of the piezoelectric layer is reduced in size. This results in a deformed or rather shortened piezoelement.

If the piezoelement created in this way is activated by an electrical field strength in the direction of polarity (parallel  
25 to the stacking direction), all domains both inside and outside the partial volume of the piezoelectric layer are switched approximately parallel to the direction of polarity. The piezoactuator in the region of the partial volume of the piezoelectric layer remains under compressive tension during this  
30 switching process. However, an increased displacement is measured in the stacking direction of the piezoelement. The increased displacement is the result of an increased  $d_{33}$  value.

In a particular embodiment, a plurality of force introduction surfaces are distributed over the piezoelectric layer in such a

way that the introduction of force causes a bending of the piezoelectric layer. For example the piezoelectric layer is a piezo-ceramic layer made from lead zirconate titanate. The bending initiated by the introduction of force results from an elastic deflection of the piezoelectric layer. If the force introduction surfaces, a thickness of the piezo-ceramic layer and the introduced force are suitably matched, a ferro-elastic deflection can be superimposed on the elastic deflection. A displacement which can be measured on the pretensioning device consists of a reduction in the deflection, an increase in the thickness of the piezo-ceramic layer due to 90° domain switching and an increase in the thickness of the layer due to the normal piezo effect. Relative to an initial thickness of the piezoelectric layer,  $d_{33}$  values of up to 15 000 pm/V are measured for a typical field strength of 1 kV/mm. This corresponds to an increase in displacement by a factor of 10 relative to previous actuator solutions.

A particular embodiment uses a partial volume extending along an entire thickness of the piezoelectric layer. A partial volume is created extending from one surface section of the piezoelectric layer to the other surface section. The partial volume pervades the entire piezoelectric layer in the thickness direction.

It is preferable for virtually complete polarization to be generated transverse to the stacking direction in this partial volume. The mechanical compressive tension causes almost complete domain switching transverse to the incoming compressive tension to be reached or exceeded in the partial volume. The compressive tension to be applied for this purpose depends on the piezoelectric material used in the piezoelectric layer. The compressive tension typically decreases in direct proportion to the decrease in the Curie temperature  $T_c$  or the coercive field strength  $E_c$  of the piezoelectric material.

In a particular embodiment, at least one of the designs chosen for the pretensioning device and/or piezoelement for generating

the force introduction surface takes the form of a spherical cup (spherical cap), frustum of a cone, cuboid, ring and/or cylinder. A prism is also possible. These designs in particular enable force introduction surfaces to be produced in both pointlike and stripe form. Pointlike means that the force introduction surface can be described by a circular or near circular surface. Such a force introduction surface, as also in the case of a ring, can be not only round but also oval or square. For example the pretensioning device has a stamp in the form of a cuboid with a square base surface area or in the form of a cylinder with a round base surface area. These base surface areas are used to transfer the mechanical compressive pretensioning to the piezoelement. The mechanical compressive pretensioning corresponding to the base surface area of the stamp is introduced via a round or square force introduction surface of the piezoelectric layer in the partial volume of the piezoelectric layer. If the cuboid has a rectangular base surface area, the force is introduced along a stripe-shaped force introduction surface into a correspondingly shaped partial volume of the piezoelectric layer. In the case of a cylinder it is also possible for the force not to be introduced via a base surface area but rather via an area of the cylindrical surface. This is then typically a line-shaped force introduction surface.

It is also possible for the force introduction surfaces to be produced with the aid of a structured electrode layer of the piezoelement. Structured electrode layers enable the force to be introduced into the piezoelectric layer at specific locations only. The introduction of a force produces domain switching exclusively at these locations. All known micro-structuring methods may be used for structuring the electrode layer.

In a particular embodiment, a plurality of partial volumes are generated in the piezoelectric layer. In this case the partial volumes are preferably separate from one another. This means that switching of the polarization of the domains is generated transverse to the stacking direction via a plurality of force

introduction surfaces in the piezoelectric layer. In this case preferably the same compressive tension is introduced via the force introduction surfaces. This typically means that when the force introduction surfaces are the same size, equal force is brought to bear on each of the force introduction surfaces via the pretensioning device.

In particular there are at least three force introduction surfaces, evenly distributed over the surface section of the piezoelectric layer. With three evenly distributed force introduction surfaces, it is relatively easy to introduce the same compressive tension into the partial volumes. The force is increased due to the enlargement of the total force introduction surface. Greater force must be exerted for the purpose of force introduction. However, there is greater force to draw upon.

In a particular embodiment there are at least three force introduction surfaces, arranged in a row on the surface section of the piezoelectric layer. With this arrangement it is for instance possible for stripe-shaped force introduction surfaces to be distributed parallel to one another over the surface section. Another possibility is for a plurality of pointlike force introduction surfaces to form a matrix of force introduction surfaces. This then results in a corresponding matrix of partial volumes in the piezoelectric layer.

The force introduction surfaces arranged on surface sections of the piezoelectric layer which face away from one another can be different in both shape and size. For example the force introduction surface on one of the surface sections is pointlike. However the force introduction surface on the other surface section can take the form of a stripe.

In a particular embodiment, surface sections of the piezoelectric layer which face away from one another have virtually identical and/or differently shaped force introduction surfaces for the purpose of creating a partial volume extending in the thickness direction. Virtually identical in this case means that the force

introduction surfaces are the same size to within 10%.

Differently shaped force introduction surfaces exist when for instance the force introduction surface on one surface section of the piezoelectric [layer] is pointlike and the other force

5 introduction surface on the other surface section is ring-shaped. These force introduction surfaces are arranged one over the other in such a way that the pointlike force introduction surface is in the center of the ring-shaped force introduction surface.

In a particular embodiment, the thickness selected for the  
10 piezoelectric layer is in the range 20  $\mu\text{m}$  to 200  $\mu\text{m}$  inclusive. It has been shown that at this layer thickness the application of even a small force brings about a significantly increased  $d_{33}$  value.

In a particular embodiment, the extent of the force introduction  
15 surface virtually corresponds to the thickness of the piezoelectric layer. In a typical example the extent is a diameter or edge length of the force introduction surface. In the case of the combination of pointlike and ring-shaped force introduction surfaces described above, however, a diameter of the  
20 ring-shaped force introduction surface is significantly greater. The diameter of the ring typically comes to 500  $\mu\text{m}$ . A diameter could even be as large as 1 mm.

In a particular embodiment, a plurality of piezoelements are stacked one over the other. In this case preferably at least two  
25 piezoelements are stacked over one another in such a way that force introduction surfaces of the piezoelements are arranged more or less flush one over the other. The partial volumes of a given piezoelectric layer are arranged one over the other in the stacking direction over the partial volumes of the piezoelectric  
30 layer of further piezoelements. This produces not only an unusually high displacement value for a given individual piezoelement, but also a piezoactuator with extremely large displacement. Any displacement is amplified as a result. The force that has to be applied in order to produce a large



displacement in the volume of the piezoelectric layers is thus relatively small.

In summary the invention provides the following advantages in particular:

- 5     • The way the force is introduced into a partial volume of the piezoelectric layer produces a piezoelement having a significantly greater displacement. This makes it possible to produce for instance a micro-actuator with an overall height of 1 mm and a displacement of 10  $\mu\text{m}$ .
- 10    • At half the no-load displacement of a micro-actuator a working force of 10 - 20 cN can be obtained.
- The force and mechanical work can be amplified by suitably stacked piezoelements and used for a plurality of applications.
- 15    • By linking piezo-ceramic multi-layer technology, micro-structuring and micro-mechanics, the invention provides solutions for a plurality of application areas (micro-pumps, micro-valves, micro-motors, etc.).

20    The invention will be described below in greater detail with the aid of several examples and the associated figures. The description of the invention discloses individual embodiments thereof which can be combined with one another in any form. The figures are diagrams and are not drawn to scale.

25    Figures 1 to 7 each show a section of a different piezoactuator as a side-view seen in cross-section.

Figures 8 to 10 each show a section of a piezoelectric layer having force introduction surfaces, looking down on the piezoelectric layer from above.

30    Figure 11 shows a perspective view of a piezoactuator in which a stripe-shaped force introduction surface has been

produced.

Figure 12 shows a piezoelement constructed in multiple layers.

The piezoactuator 1 according to Figures 1 to 9 has in each case at least one stacked piezoelement 2 formed from two electrode layers 7 and 8 arranged one over the other along the one stacking direction 10 of the piezoelement 2 and one piezoelectric layer 4 arranged between the electrode layers 7 and 8. The piezoelectric layer 4 consists of a soft PZT (lead zirconate titanate). The Curie temperature  $T_c$  is around 170°C. The coercive field strength  $E_c$  of the soft PZT is 0.5 kV/mm. The thickness 6 of the piezoelectric layer 4 is around 120  $\mu\text{m}$ .

The piezoactuator 1 has in each case a pretensioning device 15 for introduction of force into a partial volume 5 of the piezoelectric layer 4. A force 32 is introduced into the partial volume 5 of the piezoelectric layer 4 via the force introduction surfaces 13 and 14. The force introduction surfaces 13 and 14 are arranged on the surface sections 11 and 12 of the piezoelectric layer 4 facing the pretensioning device 15. The surface sections 11 and 12 are thus facing away from one another. At least one of the force introduction surfaces 13 or 14 is smaller than the associated surface section 11 or 12 of the piezoelectric layer 4.

For the purpose of creating the force introduction surfaces 13 and 14, the pretensioning device 15 is mechanically in contact with the electrode layers 7 and 8. The force introduction surfaces 13 and 14 of the surface sections 11 and 12 of the piezoelectric layer 4 are generated indirectly via the electrode layers 7 and 8. An extent of the force introduction surfaces 13 and 14 corresponds mainly to a respective mechanical contact surface between the pretensioning device 15 and the corresponding electrode layer 7 and 8.

The force introduction surfaces 13 and 14 are distributed over the piezoelectric layer 4 in the stacking direction 19 of the piezoelement 2 in such a way that the introduction of force

generates bending of the piezoelectric layer 4.

According to Figure 1 the pretensioning device 15 has at least one spherical cup 18 and at least one support ring 17 (cf. Figure 8, reference numbers 23 and 23'). The support ring 17 has the cross-section of a spherical cup. The support ring 17 is connected to a base 16 of the pretensioning device 15. The force 32 to be introduced into the partial volume of the piezoelectric layer 4 is transmitted to the spherical cup 18 with the aid of a spring (not shown). The support ring 17 and the spherical cup 18 are positioned opposite one another and arranged so that they are in mechanical contact with one of the electrode layers 7 and 8 in each case. The spherical cup 18 leads to a pointlike force introduction surface 14. The diameter of the pointlike force introduction surface is about 50  $\mu\text{m}$ . The support ring 17 leads to a ring-shaped force introduction surface 13 having a diameter of around 500  $\mu\text{m}$ . The spherical cup 18 and the ring 17 are thus arranged in such a way that the pointlike force introduction surface 14 is arranged in the center of the ring-shaped force introduction surface 13. Applying a compressive tension causes a force 4 to be introduced into the partial volume 5 of the piezoelectric layer 4 via the force introduction surfaces 13 and 14. As a result, a switching of the polarization 27 of the domains takes place in the partial volume 5 so that the polarization is transverse to the stacking direction 10. The partial volume 5 extends in the stacking direction 10 of the piezoelement 2 along the entire thickness 6 of the piezoelectric layer 4. Virtually complete polarization takes place in the partial volume 5. Unlike the previous example, the pointlike force introduction surface 14 is generated according to Figure 2 with the aid of a frustum of a cone 20 and according to Figure 3 with the aid of a cylinder 22. The support ring 17 has according to Figure 2 the cross-section of a frustum of a cone 19 and according to Figure 3 the cross-section of a cylinder 21. In a further embodiment according to Figure 11, force introduction surfaces 24 and 24' are generated with the aid of cuboids 30 and 31 having a rectangular base surface area, and are arranged in

sequence 25 or 25' (cf. Figure 9).

According to Figure 4, both the pretensioning device 15 and the piezoelement 2 have cylinders 22 and 21 with a pointlike base surface area for the purpose of generating the force introduction surfaces. The cylinder 21 of the piezoelement 2 is produced with the aid of a structured electrode layer 9. The cylinders 22 of the pretensioning device 15 and the cylinders 21 of the piezoelement 2 are offset from one another relative to the stacking direction 10. The materials in the piezoelectric layer and the electrode layers are selected to enable the stack to bend. This makes it possible to obtain a particularly large increase in displacement when the compressive tension is applied.

Figure 5 shows a further embodiment in which a plurality of cylinders applied to the surface sections 11 and 12 are arranged in a row 25. If the base surface areas of the cylinders are stripe-shaped, this results in stripe-shaped force introduction surfaces 24 and 24' (Figure 9). The force introduction surfaces 24 and 24' are offset from one another. Figure 10 shows a variant of the stripe-shaped force introduction surfaces 24 and 24'. The stripe-shaped force introduction surfaces 24 and 24' are in each case connected with one another transverse to the lengthways direction of the stripes by bridging pieces. The force is introduced into the piezoelectric layer 4 in the manner of a mesh.

A further embodiment is shown in Figure 8. A plurality of pointlike force introduction surfaces 23 are distributed over a surface section 11 and a plurality of ring-shaped force introduction surfaces 23' are distributed over the other surface section 12 of the piezoelectric layer 4 in the form of a matrix 26 and 26' in each case.

Figures 6 and 7 show two typical embodiments in which two piezoelements 2 are stacked in such a way that the force introduction surfaces 13, 14 of the piezoelements 2 are arranged flush one over the other. According to Figure 6 a structured

metal foil 28 is placed between the piezoelements 2 for the purpose of introducing the force into the piezoelectric layers 2. On the other hand Figure 7 shows an extension of the typical embodiment according to Figure 4. The electrode layers 9 have at least some cylinders for introducing the force. The electrode layers 9 are structured. An intermediate metal foil 29 is arranged between the structured electrode layers 9 of the stacked piezoelements 2 for the purpose of adapting a frictional connection.

- Further embodiments result from using piezoelements 3 constructed in multiple layers, in which a plurality of electrode layers 7 and piezoelectric layers 4 are arranged alternately one over the other (Figure 12). According to a further embodiment the outer electrode layers 7 are structured electrode layers 9.
- The test results listed in Table 1 were obtained on the basis of the piezoactuator 1 according to Figure 1. A static force of 0.7 N was applied to the piezoelement 2. The piezoelectric loading constant  $d_{33}$  was determined as a function both of the piezo-ceramic material and of the thickness 6 of the piezoelectric layer 4, at an electrical field strength of 1 kV/mm. Values of up to 15,000 pm/V may be obtained for  $d_{33}$ .

**Table 1:**

Test No. 1	Piezo-ceramics	Curie temperature	Coercive field strength	Test thickness	$d_{33}$
		[°C]	[kV/mm]	[ $\mu$ m]	[pm/V]
1	Soft PZT	330	1.0	1000	650
2	Soft PZT	330	1.0	110	2200
3	Soft PZT	170	0.5	1000	1150
4	Soft PZT	170	0.5	260	1600
5	Soft PZT	170	0.5	120	15000
6	Soft PZT	120	0.3	1000	1400
7	Soft PZT	120	0.3	160	3500